in a steel angle of 75 x 75 mm (2.95 x 2.95 in.), 8 mm (0.31 in.) thick, and 1030 mm (40.55 in.) long (refer to Fig. 3) for the German angle test. Since their manufacturing, these specimens were kept at open air and exposed to a halogen lamp irradiation [150 W (0.2 Hp)] to simulate sun warming. The lamp was placed at 100 mm (3.94 in.) from the upper surface of the angle specimens. In this way, the concrete surface temperature after 4 hours kept permanently at 77 ± 1 °C (171 ± 2 °F).

RESULTS AND DISCUSSION

Slump flow

First, properties of the fresh concrete other than slump were evaluated, since in this case the slump value is not relevant due to very fluid concrete. Therefore, the attention was focused on the measurement of the slump flow, which is the mean diameter, Φ_{fin}, of the slumped concrete. The elapsed times to gain the mean diameter of 500 mm (20 in.), t_{500}, as well as the final configuration, t_{fin}, were also determined.

As shown in Table 5, all concretes had enough deformability under their own weight (strictly related to the value of the mean diameter), and adequate viscosity (related to the value of the elapsed time to stop), which is necessary to avoid segregation of coarse aggregate particles. Neither the presence of a halo of cement paste around the slumped concrete nor the so-called 'sombrero effect' were observed.

V-funnel test

As shown in Table 5, the time elapsed for the SCCs passing trough the V-funnel was included in the range 5-8 seconds in all cases, widely within the acceptance limits.

L-box test

To evaluate the filling capacity of highly congested structural members, further tests were carried out by means of L-box with horizontal steel bars. The results obtained are reported in Table 5.

All concretes showed good, in some cases excellent, results in terms of mobility through narrow sections, particularly in the presence of the recycled-concrete powder (RP mixtures).

Concerning the flow-segregation, separation between the coarse aggregate particles and the surrounding cement paste was never observed.

Compression test

Compressive strength was evaluated according to Italian Standards UNI EN 12390-3 on cubic specimens, which were tested at right angles to the position of casting. Therefore, the bearing faces were sufficiently planar and smooth as to require no capping or grinding. The specimens were loaded at a constant strain rate until failure.

The behavior of concrete under compression was studied at curing times of 1, 7, and 28 days and the results obtained are reported in Fig. 4. The target class strength of 45 MPa (6500 psi) was reached in every case. In particular, except for the mixtures containing PVA fibers, in spite of higher dosage by volume, the mean compressive strength after 28 days of curing was approximately 60 MPa (8700 psi).

Flexure test

Flexural strength was evaluated according to Italian Standards UNI EN 12390-5 on prismatic specimens by calculating the maximum tensile stress reached at the bottom of the middle cross section of the tested specimen, that is the modulus of rupture (MOR in MPa). MOR was obtained as follows

$$MOR = \frac{3}{2} \cdot \frac{L \cdot d}{e^3} \qquad (1)$$

where *L* is the maximum load applied (N), *d* is the distance between the supports [400 mm (15.75 in.)], and *e* is the side of the specimen square cross section [100 mm (3.94 in.)].

Flexural behavior of concrete was evaluated at curing times of 1, 7, and 28 days and the results obtained are reported in Fig. 5. These results show the effectiveness of steel fibers in improving the flexural behavior of concrete (enhanced in this case by the particular hooked shape of the fibers, refer to Fig. 2). However, also the SCC mixtures prepared with polymeric fibers (PVA or PPHT) showed satisfactory performance under flexure.

Static modulus of elasticity and toughness

Static modulus of elasticity was determined under compression on cylindrical specimens [300 mm (11.81 in.) high with a diameter of 100 mm (3.94 in.)], according to Italian Standards UNI 6556.

In addition, toughness was evaluated by calculating the area under the stress-strain curve obtained under compression, even if, according to ASTM C 1399, a flexural test should be better used for toughness measurements on fiber reinforced concrete. Two values of toughness were determined: one was calculated up to the strain related to the maximum strength of concrete and it was called A-peak; the other one (called A-0.45%), was calculated up to a strain equal to 0.45% (generally higher than the previous strain).

Results obtained after 28 days of curing are reported in Fig. 6. Values of elastic static modulus were in the range predictable for ordinary concrete on the basis of the concrete strength class. In particular, the different Young modulus value of the fibers (refer to Table 3) does not seem to affect the values of static elastic modulus of concretes. Toughness of SCC was always quite high, independently of the strain considered, and particularly for those mixtures prepared with steel or PPHT fibers. In particular, the ratio between A-0.45% and A-peak, representing the post-cracking behavior, is approximately 2.5 for all the mixtures.

Drying shrinkage test

Figure 7 shows the results obtained up to 180 days. A drying shrinkage lower than 550 μm/m ($550 \cdot 10^{-6}$) can be predictable after 1 year of exposure to a relative humidity of about 50% at 20 °C (68 °F) for all the SCC mixtures. The effectiveness of fibers addition (whichever the type) in counteracting drying shrinkage of concrete is quite evident, considering that for a concrete with the same mixture composition without fibers, a drying shrinkage of about 800 μm/m ($800 \cdot 10^{-6}$) after six months can be predicted on the basis of data reported in the literature.[13]

German Angle test

This method for evaluating restrained shrinkage of concrete was developed by the Technical Academy Aachen in Germany and adopted as the Technical Test Regulations (TP BE-PCC) by Highway Construction Department of the Federal Ministry of Transport.[14] In this work, the German angle test was carried out under a severe exposure condition (halogen lamp irradiation) in order to simulate the effect of rapid water evaporation (due to dry wind and/or sun warming) on the plastic shrinkage of early-age concrete.

Only the two concrete mixtures prepared with steel fibers showed very light micro-cracking due to plastic shrinkage (age of cracking less than one day) while the other four mixtures containing polymeric fibers did not show any appearance of cracks.

CONCLUSIONS

All concretes, which were prepared for manufacturing thin pre-cast elements, met both the self-compaction requirements, while fresh, and the mechanical requirement of 45 MPa, (6500 psi) when hardened.

The fibers addition proved to be very effective in counteracting both early age cracking (particularly PVA and PPHT fibers) and delayed drying shrinkage (particularly steel fibers) of self-compacting concrete, which are usually a problem for this material, rich in powders (particularly cement), and poor in the coarse aggregate fraction.

Concerning further durability aspects such as carbonation and chloride penetration depth as well as frost resistance, encouraging data are reported in a previous work dealing with a very similar FRSCC mixture with steel fibers.[15]

Moreover, the addition of hooked steel fibers proved to be very effective in improving the mechanical behavior of self-compacting concrete in general, while maintaining excellent fresh concrete behavior due to the addition of recycled concrete powder as well as limestone powder.

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Table 1—Chemical composition and fineness of materials passing the sieve ASTM No. 100

		Cement	Recycled concrete powder	Limestone powder
Blaine fineness, m^2/g (in^2/lb)		0.42 (1.44)	0.73 (2.50)	0.61 (2.08)
Oxides, %	SiO_2	29.67	84.99	38.70
	Al_2O_3	3.74	4.47	8.02
	Fe_2O_3	1.80	3.91	3.34
	TiO_2	0.09	0.11	0.12
	CaO	59.25	2.94	40.61
	MgO	1.15	1.10	2.93
	SO_3	3.25	1.30	1.20
	K_2O	0.79	0.77	1.37
	Na_2O	0.26	0.41	1.00
Loss on ignition at 1000 °C (1832 °F)		11.62	26.57	34.23

Table 2—Physical properties of the aggregate fractions

Aggregate fractions	Bulk specific gravity (SSD), kg/m^3 (t/yd^3)	Water absorption, %	Passing the 75 μm ($3 \cdot 10^{-3}$ in.) sieve, %
Natural sand	2610 (2.00)	3.1	0.9
Crushed aggregate	2660 (2.03)	2.6	0.1

Table 3—Main characteristics of the fibers used

Type of fiber	Length, mm (in)	Diameter, mm (in)	Aspect ratio, AR	Young modulus, GPa (kpsi)	Tensile strength, MPa (kpsi)
Steel	30 (1.18)	0.70 (0.028)	43	170 (24,650)	450 (65)
PVA	12 (0.47)	0.20 (0.008)	62	30 (4350)	1000 (145)
PPHT	35 (1.38)	0.62-0.69 (0.026)	51-57	3.8 (550)	600-750 (100)

Table 4—Concrete mixture proportions

Mixture	S-RP	S-LP	PPHT-RP	PPHT-LP	PVA-RP	PVA-LP
Water/Cement	0.40	0.40	0.40	0.40	0.40	0.40
Water, kg (lb)	200 (441)	200 (441)	200 (441)	200 (441)	200 (441)	200 (441)
Cement, kg (lb)	500 (1102)	500 (1102)	500 (1102)	500 (1102)	500 (1102)	500 (1102)
Natural sand, kg (lb)	1080 (2381)	1080 (2381)	1080 (2381)	1080 (2381)	1080 (2381)	1080 (2381)
Crushed aggregate, kg (lb)	420 (926)	420 (926)	420 (926)	420 (926)	420 (926)	420 (926)
Limestone Powder (LP), kg (lb)	—	70 (154)	—	70 (154)	—	70 (154)
Recycled concrete Powder (RP), kg (lb)	58 (128)	—	58 (128)	—	58 (128)	—
Steel fibers (S), kg (% by volume)	50 (0.6)	50 (0.6)	—	—	—	—
High toughness poly-propylene fibers (PPHT), kg (% by volume)	—	—	5 (0.6)	5 (0.6)	—	—
Poly-vinyl-alcohol fibers (PVA), kg (% by volume)	—	—	—	—	10 (0.8)	10 (0.8)
Superplasticizer, kg (lb)	7 (15.4)	7 (15.4)	7 (15.4)	7 (15.4)	7 (15.4)	7 (15.4)

Table 5—Rheological test results

Mixture		S-RP	S-LP	PPHT-RP	PPHT-LP	PVA-RP	PVA-LP
Slump flow test	Φ_{fin}, mm (in.)	660 (26)	700 (28)	680 (27)	680 (27)	680 (27)	680 (27)
	t_{500}, seconds	1	3	3	3	2	2
	t_{fin}, seconds	13	13	13	13	12	12
V-funnel test	t, seconds	7	5	8	7	8	8
L-box test	ΔH_{fin},* mm (in.)	60 (2.36)	65 (2.56)	40 (1.57)	60 (2.36)	30 (1.18)	50 (1.97)
	t_{stop},† seconds	16	12	19	15	21	18

*Difference in the concrete level between the beginning and the end of the box.

†Elapsed time to get the final configuration.

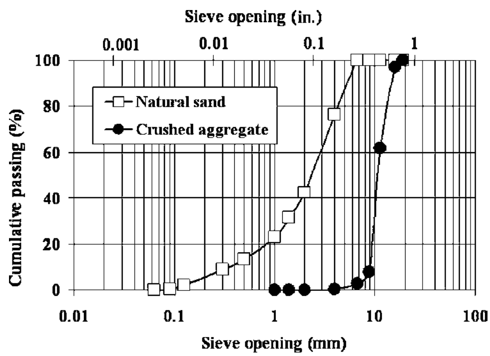

Fig. 1—Grain size distribution curves of the aggregate fractions.

Fig. 2—Fibers used: (a) steel fibers, (b) PVA fibers, and (c) PPHT fibers.

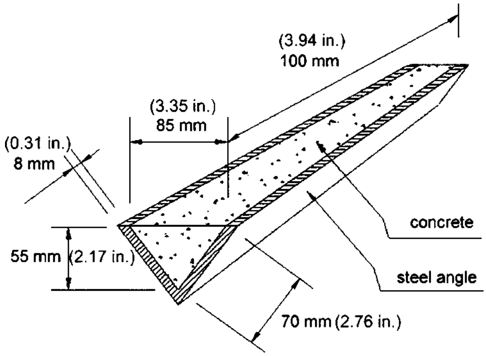

Fig. 3—Scheme of the steel angle used for German angle test.

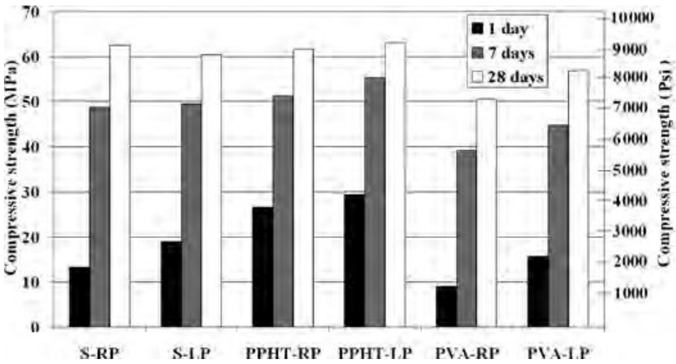

Fig. 4—Compressive strength versus curing time.

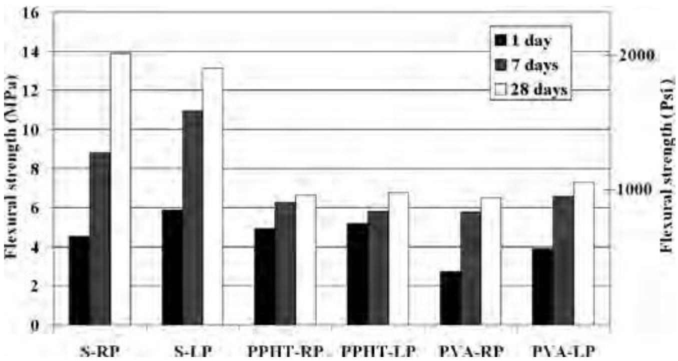

Fig. 5—Flexural strength versus curing time.

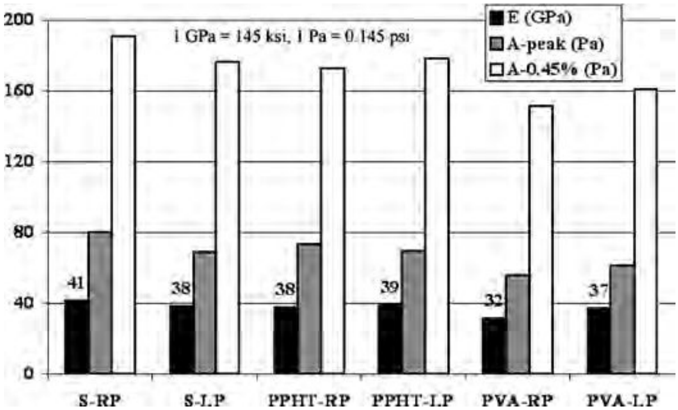

Fig. 6—Elastic modulus (*E*) and toughness values (A-peak, A-0.45%) calculated from experimental data obtained by means of compression tests.

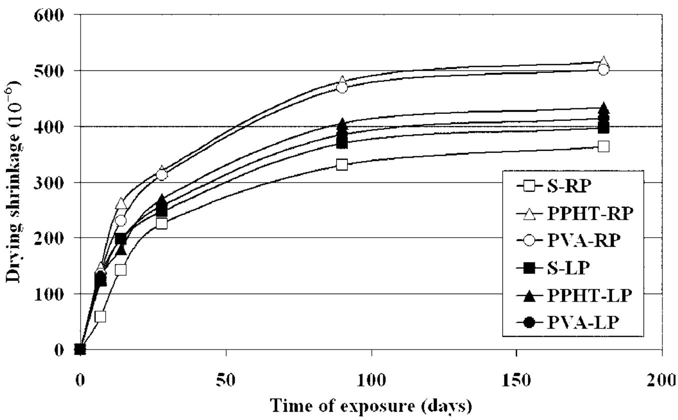

Fig. 7—Drying shrinkage measurements up to 180 days of exposure to 50% relative humidity at 20 °C (68 °F).

Investigation of the Type of Supplementary Cementing Materials on the Durability of Self-Consolidating Concrete

by M. Sonebi, S. Stewart, and J. Condon

Synopsis: Self-consolidating concrete (SCC) is designed to exhibit high deformability and moderate viscosity to maintain homogeneity and adequate stability to fill the formwork, and encapsulate the reinforcement without any mechanical vibration. Any concrete should have high impermeability and low chloride diffusion to reduce the risk of corrosion and enhance service life. In this study, the effect of the replacement content of cement by supplementary cementing materials (SCM) and fillers. Limestone powder (LSP) replacement of 15% to 30%, ground granulated blastfurnace slag (GGBS) of 40% to 60%, and pulverized fly ash (PFA) of 20% to 35% are evaluated on the durability of SCC of grade C40/50. Fresh concrete properties and development of compressive strength were also evaluated. For the durability performance, all mixtures were tested at 28 days for the air permeability, water permeability, sorptivity, and chloride diffusion which were assessed by Autoclam, and Permit tests. The chloride migration coefficient was dependent on the type SCM and filler in use. The most durable SCC mixture, taking into consideration overall properties, was found to be the one containing 20% PFA, which showed low capillary water absorption, water and air permeation, and lower ionic diffusivity in comparison to the other mixtures. In general, SCC mixtures containing GGBS exhibited inferior performance regarding air and water permeability and sorptivity, but had satisfactory chloride resistance. SCC with 50% of GGBS demonstrates the lowest chloride diffusivity.

Keywords: capillarity; chloride diffusion; ground-granulated blast-furnace slag (GGBS); limestone powder (LSP); pulverized fly ash (PFA); permeability; self-consolidating concrete (SCC).